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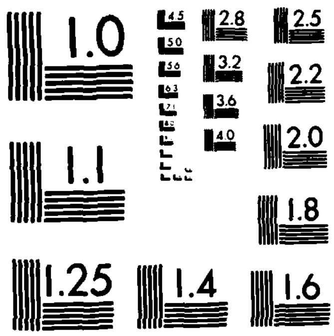

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NRL Memorandum Report 5609

The Ionization Equilibrium of Optically Thick Argon Z-Pinch Plasmas for Electron Temperatures Between 25 and 65 eV

J. P. APRUZESE, P. C. KEPPLE, AND J. DAVIS

Plasma Radiation Branch
Plasma Physics Division

July 2, 1985

This work was supported in part by the Strategic Defense Initiative Organization and the Defense Nuclear Agency under Subtask T99QMXLA, work unit 00004 and work unit title "Advanced Simulation Concepts."

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5609	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b. OFFICE SYMBOL (If applicable) Code 4720	7a. NAME OF MONITORING ORGANIZATION Defense Nuclear Agency
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code) Washington, DC 20305
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Defense Nuclear Agency 8b. OFFICE SYMBOL (If applicable) RAEV	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20305	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62715H	85-579		DN880-191

11. TITLE (Include Security Classification) The Ionization Equilibrium of Optically Thick Argon Z-Pinch Plasmas for Electron Temperatures Between 25 and 65 eV

12. PERSONAL AUTHOR(S)
Apruzese, J.P., Kepple, P.C., and Davis, J.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Interim	FROM ______ TO ______	1985 July 2	28

16. SUPPLEMENTARY NOTATION
(See page ii)

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Ionization equilibrium; Argon plasma; Gamble-II generator; Collisional pumping ,

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Calculations of the ionization balance of optically thick argon plasmas of electron temperature 25-65 eV are presented. A multistage, multilevel model of argon ions with accurate radiation transport of ~ 50 lines in the sodium, neon, and flourine-like stages forms the basis of the calculations. By comparison with similar optically thin calculations, the effects on ionization of radiative and collisional pumping of excited states of these stages is delineated. In particular, the broad temperature distribution of the neon-like stage is compressed by line photon pumping to a narrower regime of existence because of ionization from the excited states. The relevance to the 3p-3s lasing scheme in neon-like argon is briefly discussed.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Jack Davis	22b. TELEPHONE (Include Area Code) (202) 767-3278 22c. OFFICE SYMBOL Code 4720

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

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16. SUPPLEMENTARY NOTATION

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CONTENTS

THE IONIZATION EQUILIBRIUM OF OPTICALLY THICK ARGON Z-PINCH PLASMAS FOR ELECTRON TEMPERATURES BETWEEN 25 AND 65 eV

I. Introduction

Due to some recent successful experiments at Livermore,[1,2] which were preceded by a host of theoretical calculations,[3-11] considerable interest now centers upon neon-like ions in plasmas as very promising for achievement of population inversions leading to lasing in the extreme ultraviolet to x-ray regions of the spectrum. Although the first successful demonstrations used frequency-doubled neodymium laser light at 0.53 μm as a plasma driver, use of Z-pinch plasmas coupled to large pulsed power generators as a lasing medium is also highly attractive due to the large gain lengths (up to 4 cm) and immense energies (~1 MJ) available to couple to the plasma. The Gamble-II device at NRL, while of relatively modest energy, has proven to be a very efficient producer of K-shell radiation from neon plasmas[12,13]. The use of fast plasma opening switches[14] to reduce pulse risetimes has produced more orderly pinches with instabilities considerably less pronounced than those previously observed[15]. These results suggest that Gamble-II would be an excellent device to test lasing concepts on a Z-pinch. Argon, stripped to the neon-like stage, is a prime candidate for lasing given both the available machine energy and expectation of high quality pinches. It is the purpose of this Memorandum Report to investigate the plasma conditions (temperature, density, size) which will optimize the production of the neon-like stage and also the pumping of the upper lasing 3p manifold of J-sublevels. We also identify and clarify the physical mechanisms which are responsible for the functional behavior of the ionization balance and pumping of the 3p levels.

Manuscript approved April 25, 1985.

II. Description of the Atomic Model and Radiation Transport

The atomic model consists of all ground states of argon with the following excited states in the sodium-like, neon-like, and fluorine-like ions:

	State	Statistical Weight	Energy Above Ground (eV)
Ar VIII	$3p\,^2P$	6	17.695
(sodium-like)	$3d\,^2D$	10	41.219
	$4s\,^2S$	2	71.377
	$4p\,^2P$	6	77.986
	$4d\,^2D$	10	86.443
	$4f\,^2F$	14	88.841
	[n=5]	50	103.20
Ar IX	$[2p^5 3s]$	12	252.16
(neon-like)	$[2p^5 3p]$	36	270.18
	$[2p^5 3d]$	60	293.76
	$[2s2p^6 3s]$	4	329.43
	$[2s2p^6 3p]$	12	346.82
	$[2p^5\ n=4]$	192	349.81
	$[2s2p^6 3d]$	20	370.19
Ar X	$2s2p^6\ ^2S$	2	75.734
(flourine-like)	$[2p^4 3s]$	30	283.86
	$[2p^4 3p]$	90	301.96
	$[2p^4 3d]$	150	324.69
	$[2s2p^5 3s]$	24	353.97
	$[2s2p^5 3p]$	72	371.25
	$[2s2p^5 3d]$	120	393.44
	$[2p^4\ n=4]$	480	394.20
	$[2s2p^5\ n=4]$	384	435.00

The states enclosed in square brackets [ ] are composites of several states with similar energy.

The rate table associated with this model includes:

1. Photoionization rates from each ground state and each excited state. These rates were calculated using the hydrogenic approximation with Karzas and Latter[16] Gaunt factors, corrected for equivalent electrons.

2. Collisional ionization from each ground and excited state to the ground state above. These rates were calculated using the exchange classical impact parameter technique.[17]

3. Dielectronic recombination rates from all ground states to the adjacent ground state. These rates include (implicitly) the effect of the excited states[18].

4. The Einstein A coefficients were calculated by Cowan's[19] code with appropriate averages for composite levels.

5. Collisional excitation rates for dipole allowed transitions were calculated in the semiclassical impact parameter approximation[20]. For transitions with no dipole allowed component the collisional excitation rates were calculated with a distorted wave[21] code.

6. Detail balance was used to obtain the radiative recombination rates from the photoionization rates, the 3-body recombination rates from the collisional ionization rates, and the collisional deexcitation rates from the collisional excitation rates.

Radiation transport is calculated by a cell-to-cell photon coupling technique using a matrix C_{ij} for each transition which is the probability that a line photon emitted in cell i is absorbed in cell j. Details of the technique have been given previously.[22,23] The steady-state solution for the state and level populations, consistent with the radiation field, is obtained by an iteration technique.[24]

III. Results

Two argon ion densities (3×10^{18} cm^{-3} and 6×10^{19} cm^{-3}) have been chosen for the calculations. These densities represent the approximate lower and upper limits of those achieved in imploding neon gas puff experiments on the NRL Gamble-II generator. The 25-65 eV temperature regime is chosen to examine the behavior of the neon-like argon stage. The results of our calculations are presented in Figs. 1-7. In each case the ground state ionic fraction for the neon-, flourine-, and sodium-like stages is shown as a function of electron temperature. The total ion density and assumed plasma size differ from figure to figure. In Figs. 1-4, an ion density of 6×10^{19} cm^{-3} is assumed, and in the remainder of the figures the ion density used was 3×10^{18} cm^{-3}. For each chosen ion density, cylindrical plasma diameters of 1.8 mm and 0.5 mm were used, and a calculation was also performed in which all lines were assumed optically thin (equivalent to the zero-size limit). The objectives were to approximate the experimental conditions, expected with argon gas-puff implosions on Gamble II, and, through use of the optically thin calculation, to gauge the effects of radiative pumping on ionization.

Figs. 1 and 2 present the ionization curves for ion density 6×10^{19} cm^{-3} and cylindrical diameter 1.8 mm. The only difference is that, for Fig. 1, no sodium-like excited states were included in the model. Only a minor effect on the neon-like stage distribution occurs, but note that the sodium-like stage persists at higher temperatures when the calculation excludes excited states for the sodium-like stage. This is because a significant amount of ionization occurs from the excited states, and excluding them from the model inevitably results in a less ionized plasma. When the excited states are included, the flourine-like stage becomes substantially more prevalent, reflecting the extra ionization. These effects have also been previously noted for K-shell plasmas.[25]

Figures 2,3, and 4 display the effects of line opacity on argon plasma ionization, for a fixed total argon ion density of 6×10^{19} cm^{-3}. As the assumed plasma size decreases from 1.8 mm to 0.5 mm (Fig. 2 compared to Fig. 3), little effect is noted. This is due to the fact that the optical depths of the principal resonance lines are already so high (10^2-10^3) that the radiative pumping rate is saturated by collisional destruction of the line photons after a few scatterings in the lines. Therefore, since the line pumping does not change, the ionization does not change. Comparison of Figs. 5 and 6 - where the ion density is 3×10^{18} cm^{-3} - reveals this same lack of change at lower ion density. However, when the plasma is assumed optically thin in all the lines, substantial reduction of the ionization is observed. This is seen specifically by comparing Fig. 4 to Fig. 3 and Fig. 7 to Fig. 6. When there is no radiative pumping of the excited levels, there is less ionization from those levels and, therefore, a less highly ionized plasma. Experimental achievement of an optically thin argon plasma would require a characteristic size of a few microns - currently unrealizable with a Z-pinch. The optically thin plasmas also exhibit a broader distribution of the neon-like stage. This is a manifestation of the relative lack of excited state populations in these cases, allowing the characteristic "closed shell" properties of the neon-like ground state to produce the expected broad distribution closer to that seen in the coronal limit.[26]

Further insight into this last point is obtained by comparing Fig. 4 and Fig. 7. Both curves reflect optically thin calculations, the only difference being the ion density. At the lower ion density of Fig. 7, an extremely broad peak in the neon-like distribution is seen, similar to that obtained in the coronal limit by Shull and Van Steenberg[26] (also plotted) but at lower temperatures than their results. Figure 4 reveals that at higher densities the peak is narrowed even though the calculation still assumes zero optical depth at all frequencies. The reason for this difference is that excited states are populated collisionally as well as radiatively. Even though no radiative excitations occur in those calculations, the increased collisional population of the excited states at higher ion density removes some of the "closed shell" property from the neon-like stage, resulting in more ionization (from the excited states) and therefore a narrower peak further removed from the coronal limit than at the lower ion density of 3×10^{18} cm^{-3}.

Finally, we address the implications of these results for the achievement of 3p-3s lasing in neon-like Ar IX. At first it would seem that optimum plasma conditions would lie where the neon-like stage maximizes, i.e. at T_e = 35-45 eV. Actually, the optimum temperature for 3p-3s lasing is in the 50-55 eV range. Figure 8 illustrates the reason for this difference. In this figure is plotted the fraction of all particles whose energies lie above a certain threshold for a Maxwellian distribution. For Ar IX, the 3p levels are approximately 270 eV above the ground state. At T_e = 40 eV, only ~ 0.3% of the electrons are capable of exciting these levels. However, at 55 eV ~ 2% of the electrons have sufficient energy to excite the upper lasing 3p levels. This more than compensates for the reduction in neon-like ground state population. Our calculations indicate that the flourine-like resonance line complex, $2s^2 2p^5$ - $2s^2 2p^4 3d$ at 38.5Å will emit with about the same intensity as the neon-like resonance line complex $2p^6$-$2p^5 3d$ at 42Å when optimal pumping conditions are achieved for the neon-like species.

The present model does not contain enough detail in the neon-like excited state manifold to extract detailed gain behavior, and such calculations are reserved for a future report. The ionization balance calculations, however, are affected little by breaking composite levels into J-sublevels for more detailed gain calculations.

ACKNOWLEDGMENT

This work was supported by the U.S. Strategic Defense Initiative Organization and the Defense Nuclear Agency.

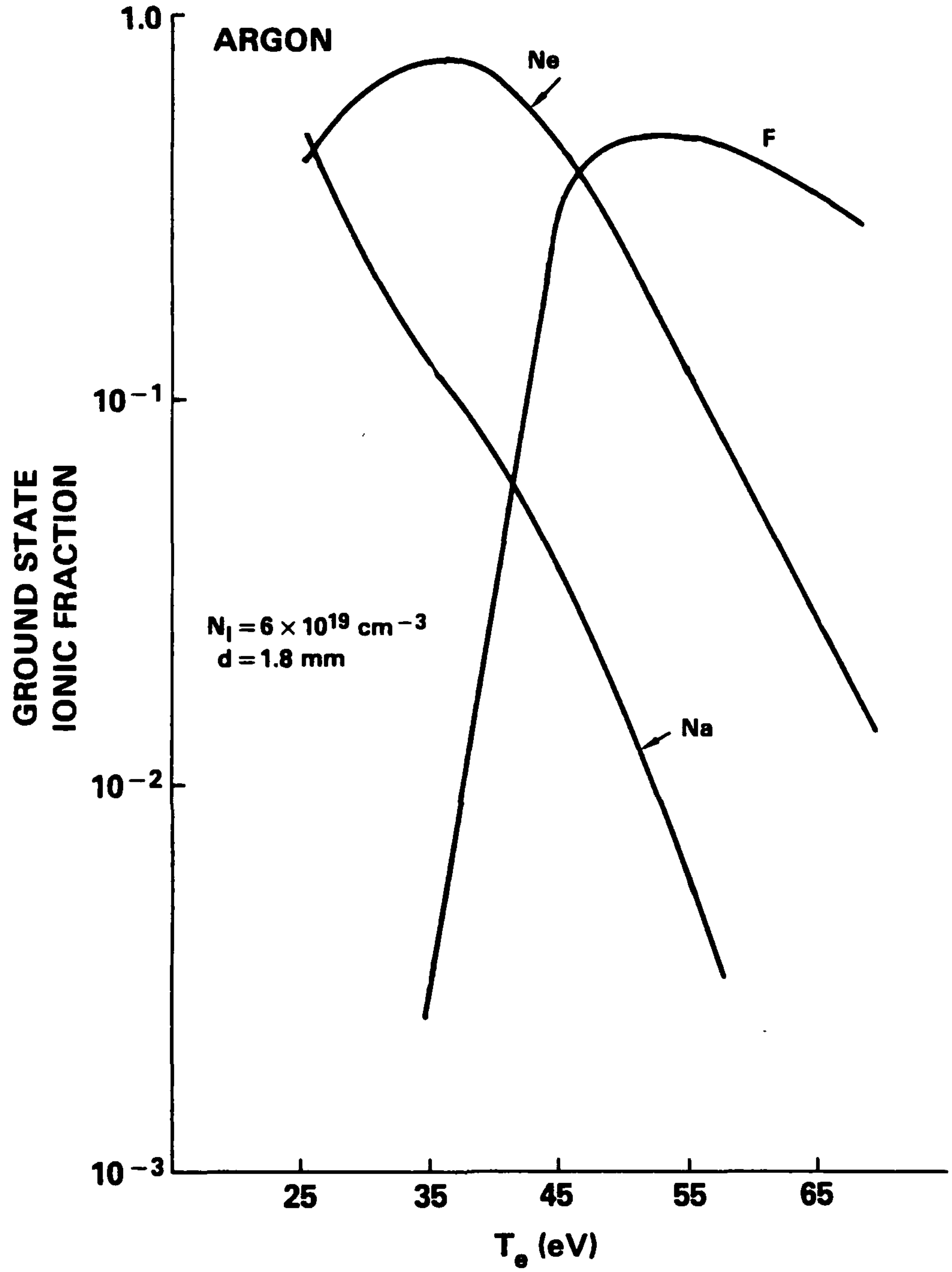

Fig. 1. The ground state ionic fractions for sodium-like, neon-like, and flourine-like argon are plotted against electron temperature for a total argon ion density of 6×10^{19} cm^{-3} and cylindrical plasma diameter of 1.8 mm. No sodium-like excited states are included in this calculation.

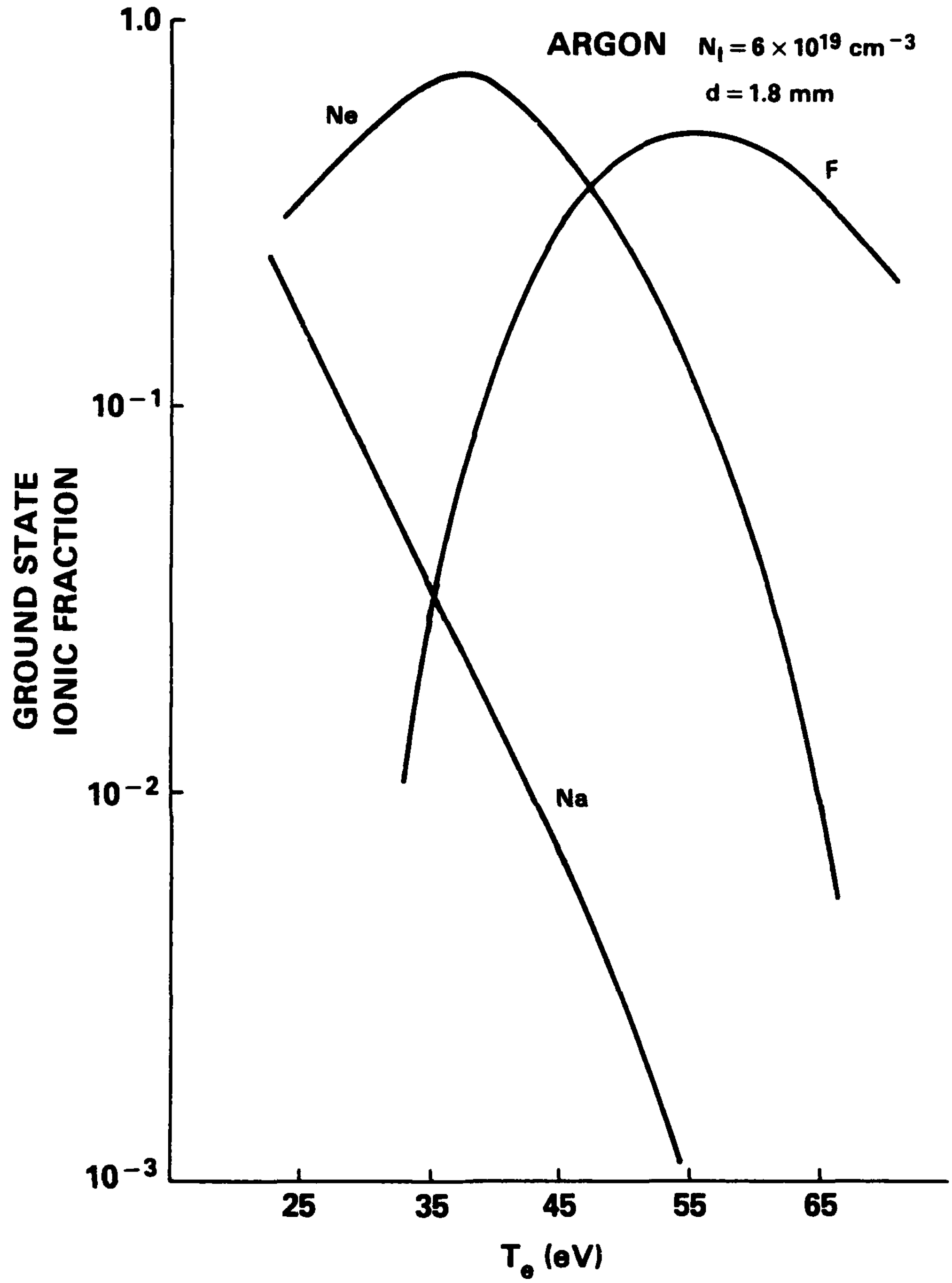

Fig. 2. As in Fig. 1, except that the sodium-like excited states described in Section II are included in the calculation.

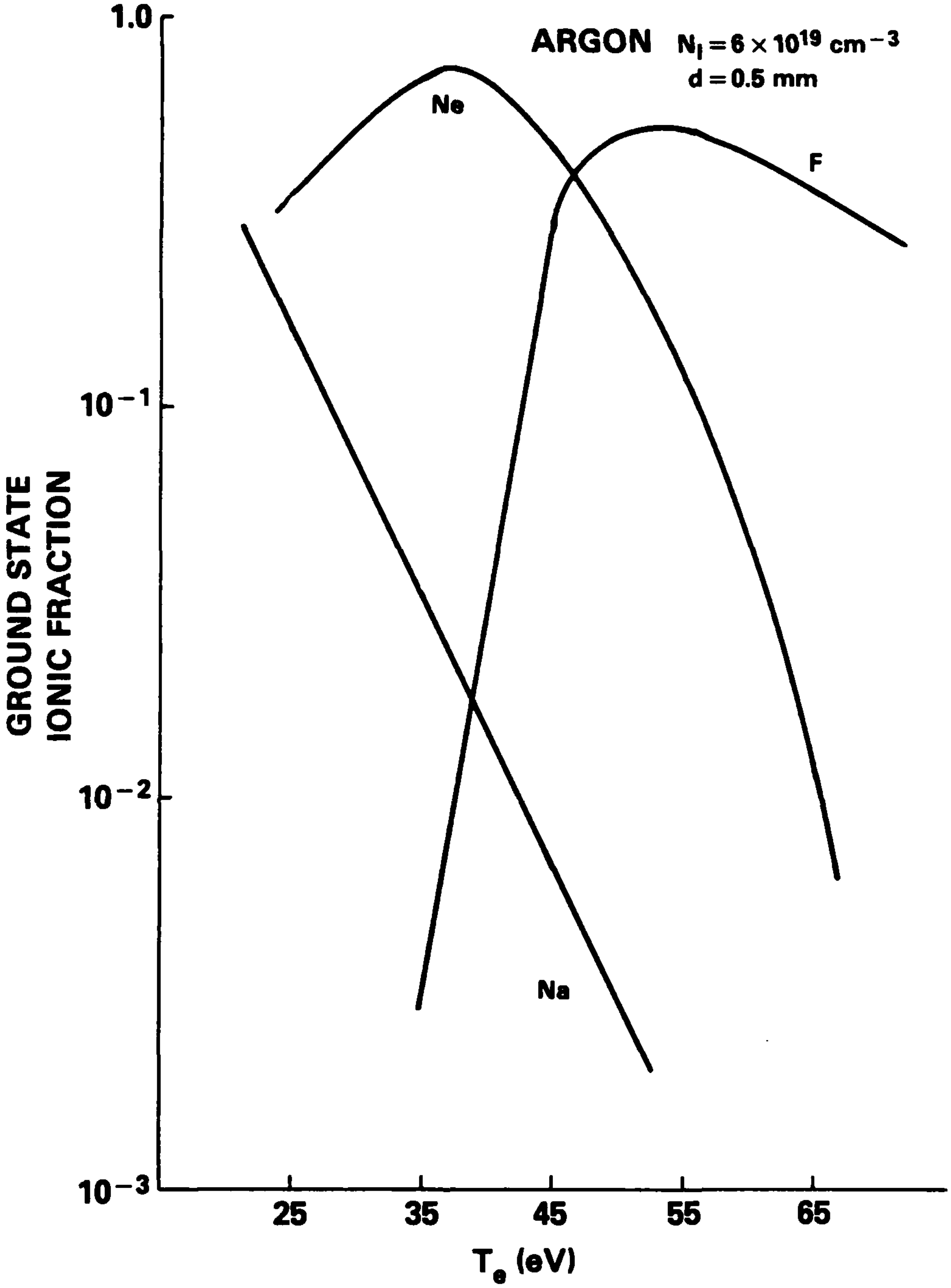

Fig. 3. As in Fig. 2, except that the plasma diameter is assumed to be 0.5 mm.

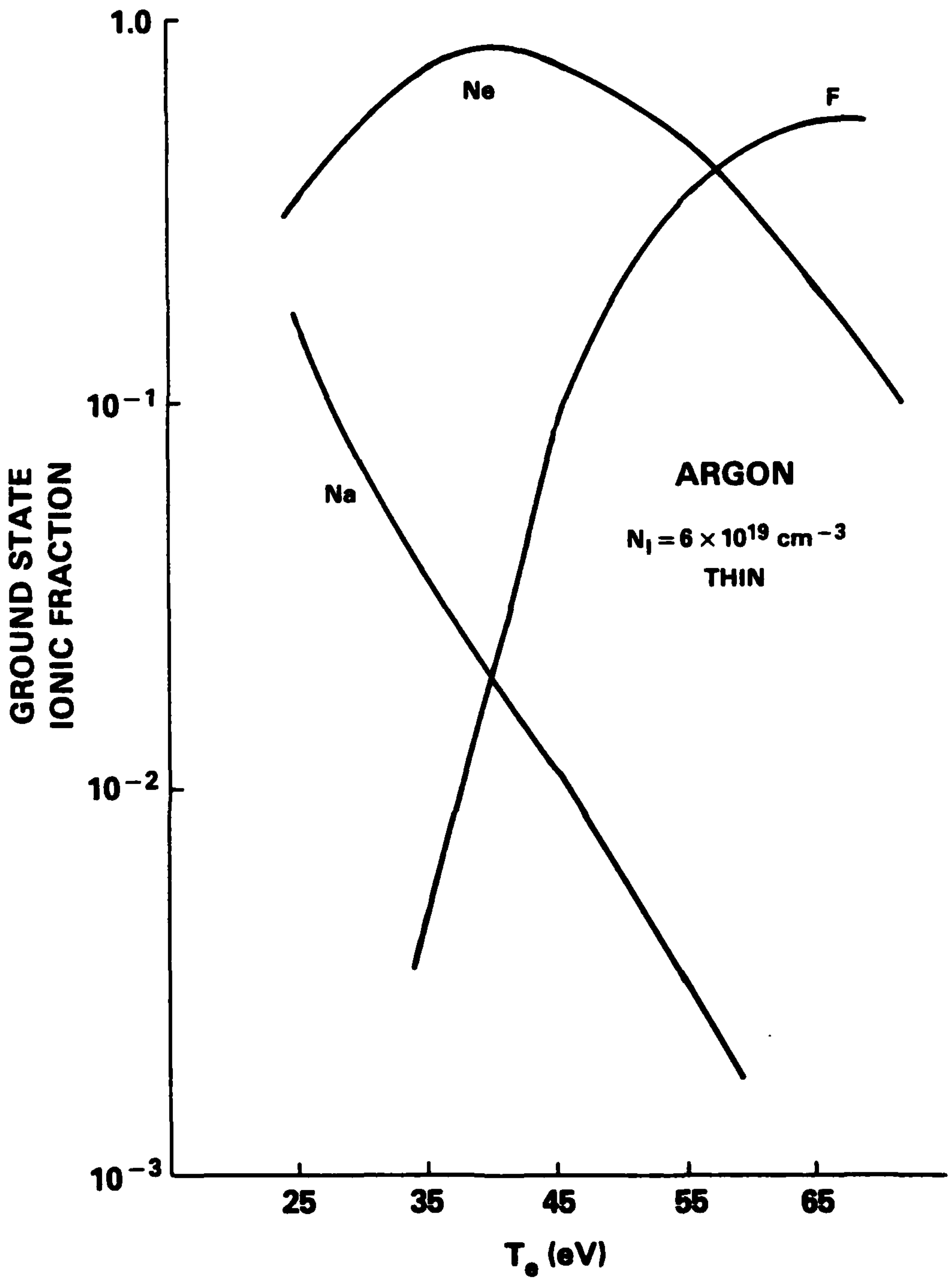

Fig. 4. As in Figs. 2 and 3, except that the plasma is assumed optically thin (zero size limit).

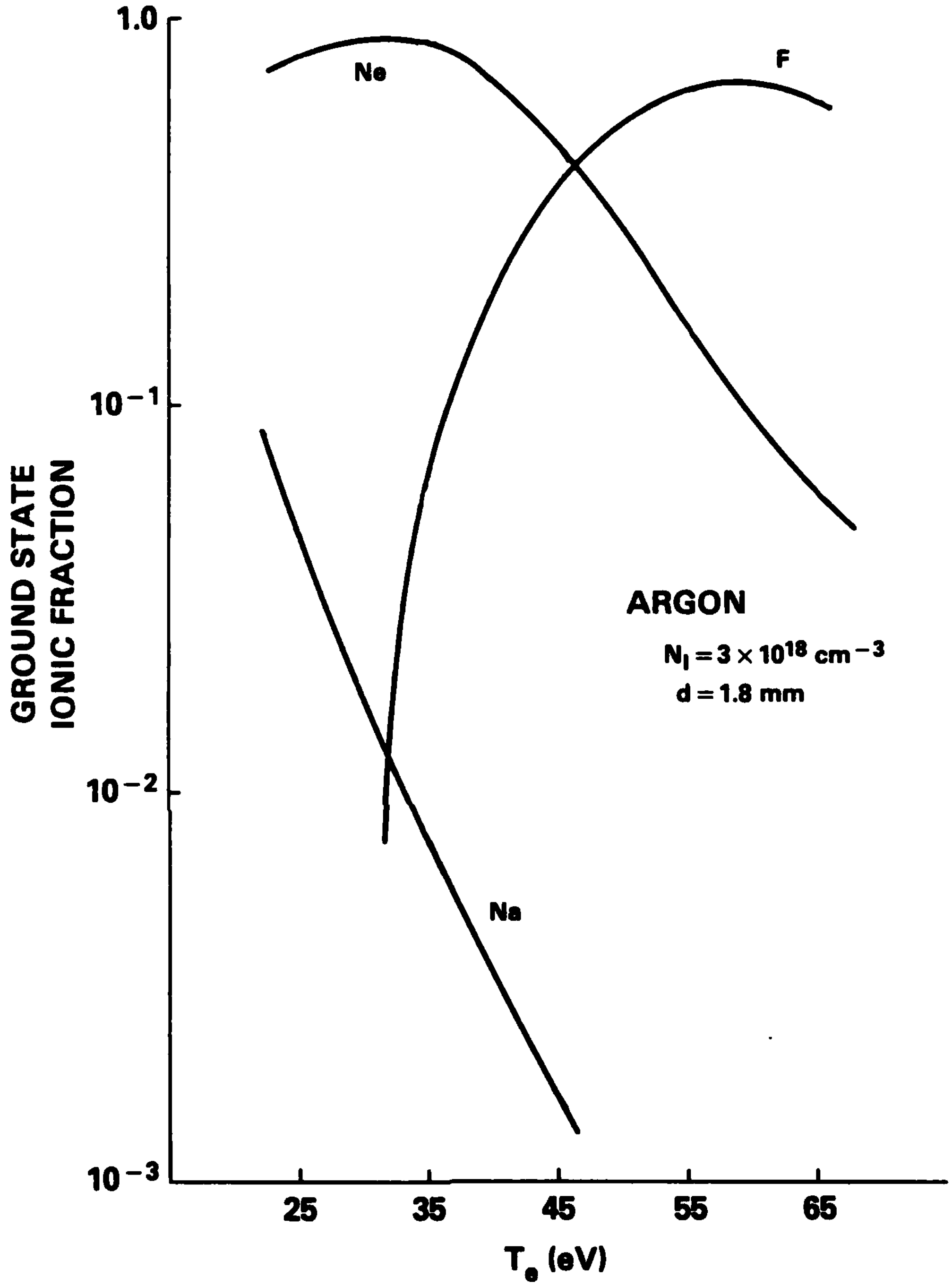

Fig. 5. The ground state ionic fractions for sodium-like, neon-like, and flourine-like argon are plotted against electron temperature for a total argon ion density of 3×10^{18} cm^{-3} and a cylindrical plasma diameter of 1.8 mm.

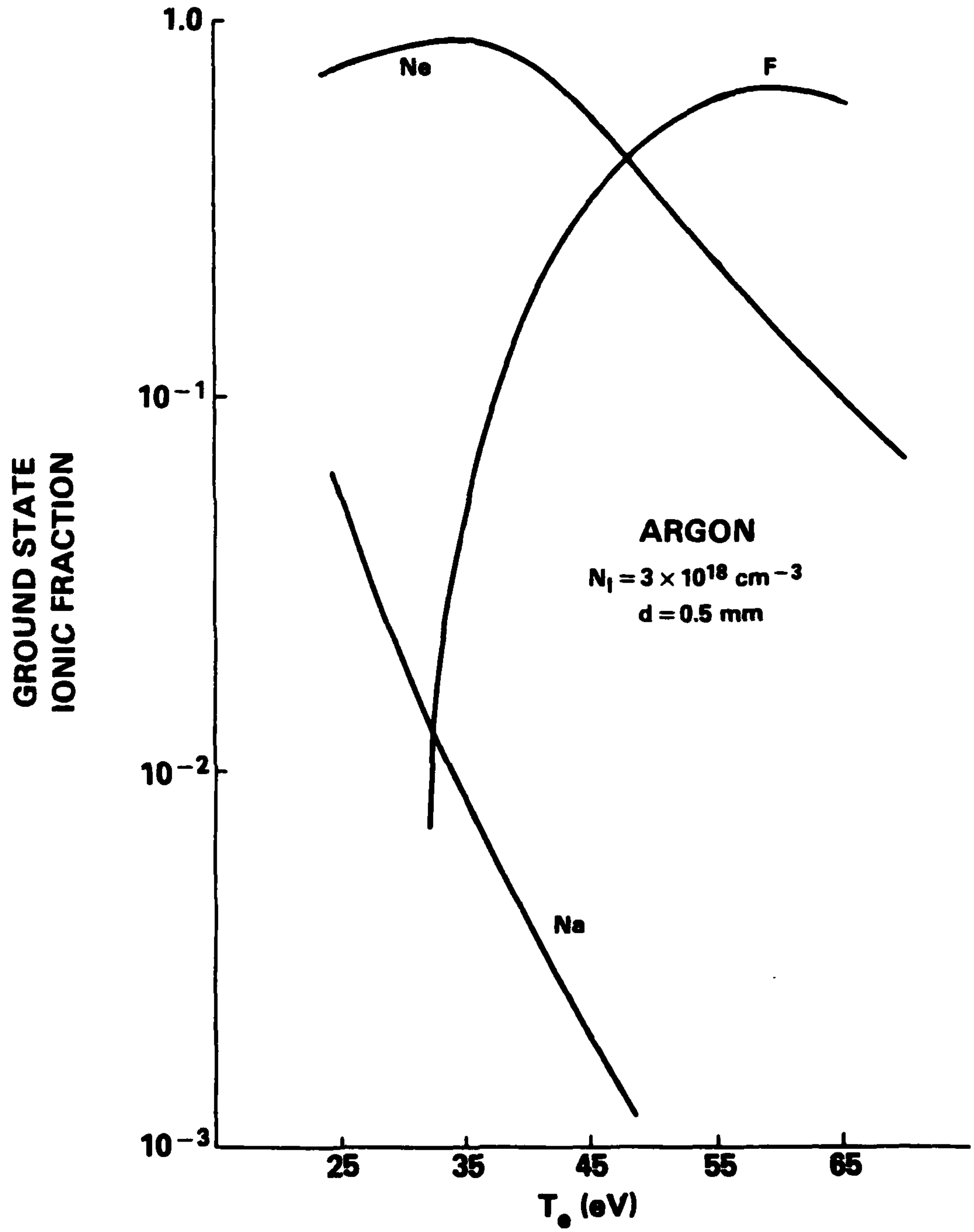

Fig. 6. As in Fig. 5, except that the plasma diameter is assumed to be 0.5 mm.

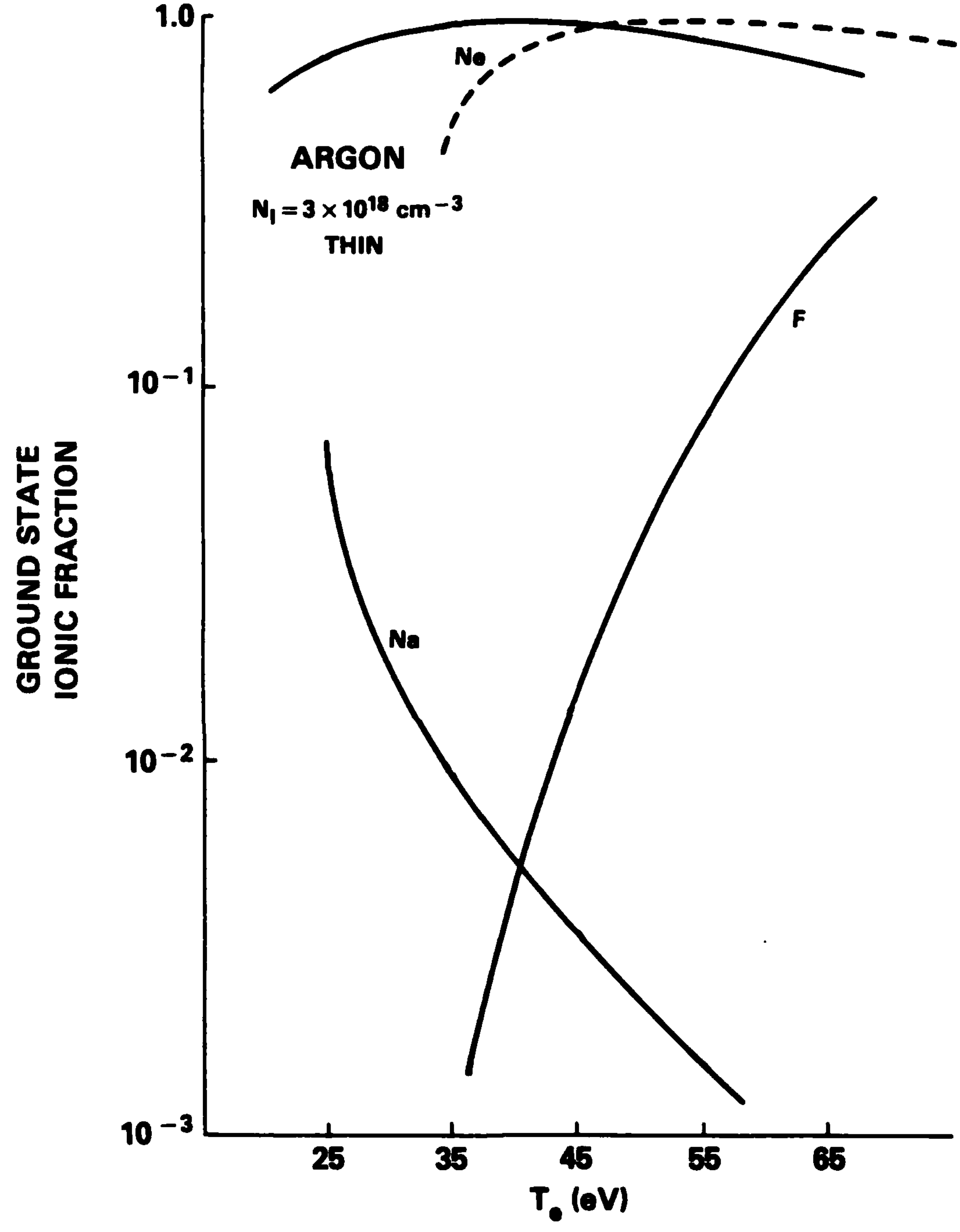

Fig. 7. As in Figs. 5 and 6 except that the plasma is assumed to be optically thin (zero size limit). The coronal equilibrum results of Ref. 26 for neon-like argon are also shown.

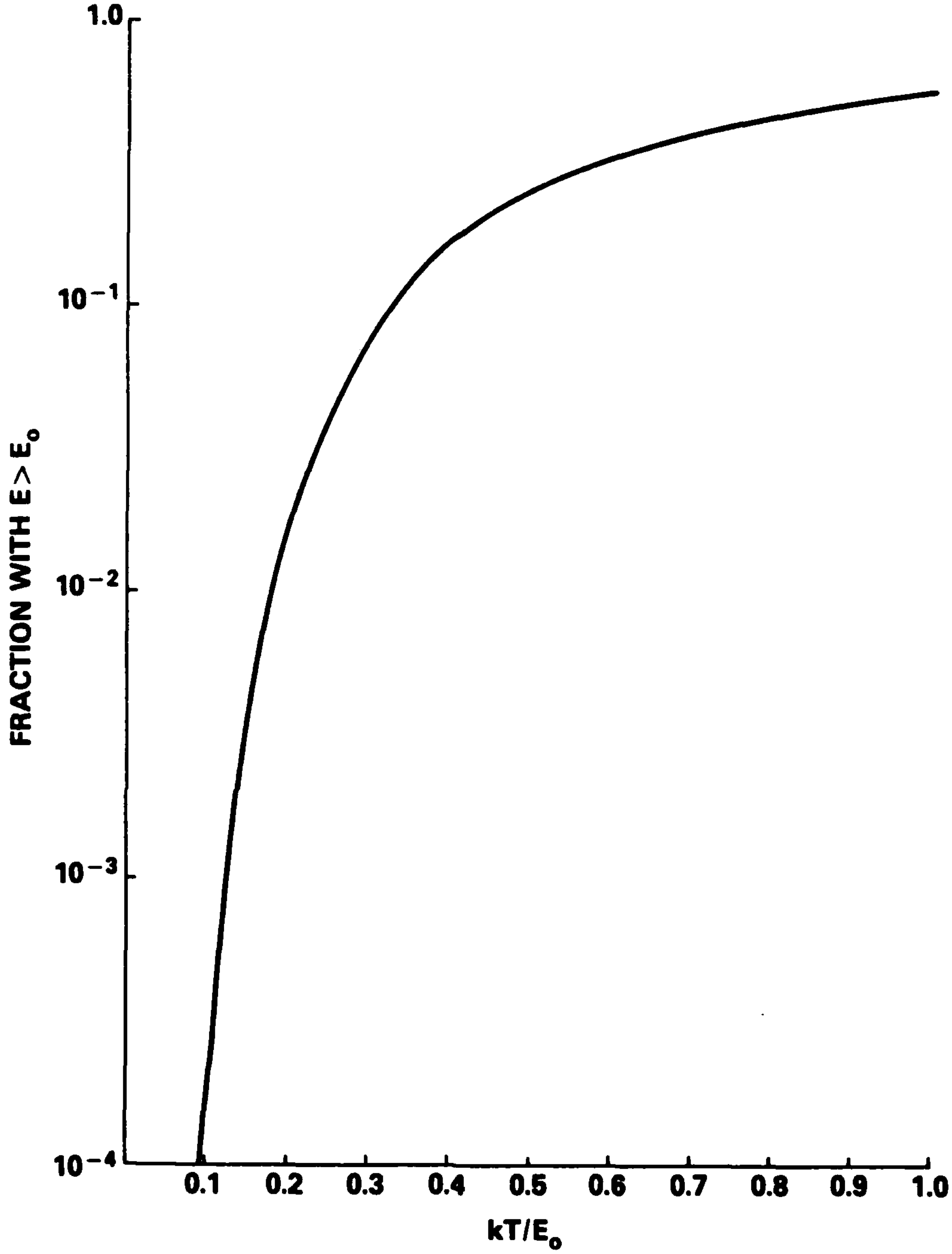

Fig. 8. The fraction of all particles in a Maxwellian distribution whose energies E lie above a threshold energy E_o is plotted against ratio of temperature to E_o.

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